MOTOR OR GENERATOR TYPE ELECTROMAGNETIC DEVICES

The present invention relates to electromagnetic devices,
that is single- or multi-phase generators and motors of

5   unlimited stroke or of limited stroke (actuators), each
device comprising, for each phase, at least two
relatively-movable sets of teeth of soft magnetic
material, one set of teeth being associated with the
stator and the other with the moving part that moves with

10 rotary or linear motion (hereinafter "rotor"). Each set
of teeth can comprise a plurality of teeth and the number
of teeth can be different between the stator and the
rotor. In the limit, one or even both sets could have
only one tooth.

15

In many devices of this type, the pitch between the teeth
is substantially constant and substantially the same for
both sets of teeth. The reluctance opposing the passage
of the magnetic field between these sets of teeth, and

20 consequently the permeance which is the inverse of
reluctance, varies during displacement. When one end of
a stator tooth and one end of a rotor tooth face each
other, they define between them an air-gap of minimum
width E. In the devices to which the invention applies,

25 the unit displacement dx (cf. Figure 5) of a rotor tooth
is parallel to the tangent to the end of a stator tooth,
thus distinguishing such devices from electromagnets
where displacement takes place in the minimum air-gap
direction.

30

Rotary or linear motion devices having the above-
mentioned characteristics can be motors, actuators, or
generators with variable reluctance, that is without a
permanent magnet, or motors, actuators, or generators

35 that are hybrid or having "polarized reluctance", that is
including at least one permanent magnet in the stator or
the rotor.

In its most commonplace rotary versions, the device
comprises a rotor that is generally cylindrical in shape,
being constituted by at least one coaxial assembly
5   comprising at least one rotor pole piece fixed on a
shaft, each pole piece of the rotor presenting a set of
teeth formed by radial teeth disposed along its periphery
at a uniform pitch. The device also comprises a stator
which comprises a magnetic circuit portion of soft
10   magnetic material, which is generally annular in shape
being disposed coaxially around the rotor, and
constituted by a peripheral portion and a plurality of
stator pole pieces. Each stator pole piece is powered by
at least one electrical coil and comprises one or more
15   teeth directed radially so as to face the teeth of the
rotor. If there are two or more teeth per pole piece,
then the teeth of the stator are disposed substantially
at the same pitch as the teeth of the rotor, one rotor
tooth and one stator tooth placed facing each other
20   defining between them a radial air-gap having a minimum
width E. Variants also exist in which the air-gap is
axial, or oblique.

Such electromagnetic devices have been known for several
25   tens of years. Hybrid types are in widespread use,
particularly in the form of two- or three-phase stepper
motors. Descriptions of such devices can be found for
example in the book "Stepping motors and their
microprocessor controls" by Takashi Kenio and Akira
30   Sugavara, Clarendon Press, Oxford, 1994, 2nd edition,
pp. 28 to 36 for variable reluctance motors, pp. 37 to 44
for hybrid motors, or in the Treatise on Electricity of
"l'Ecole Polytechnique Fédérale de Lausanne", Vol. IX,
entitled "Electromécanique" [Electromechanics], by Marcel
35   Jufer, Presses polytechniques et universitaires romandes,
§ 11.2.5 "Moteur réluctant à simple circuit" [Single
circuit reluctance motor] and § 11.2.11 "Moteur réluctant

polarisé" [Polarized reluctance motor]. Linear motion
variants correspond to rolling rotary motors out flat and
are described, for example, on page 33 of the above-
specified work by T. Kenjo and in § 11.13 in the above-
5   cited work by M. Jufer.

Numerous theoretical studies have been done on such
devices, cf. in particular the article by Marcel Jufer
and Gunter Heine "Hybrid stepper motor torque and
10 inductance characteristics with saturation effects"
published in "Incremental Motor Control Systems and
Devices (IMCSD) Proceedings", Fifteenth Annual Symposium,
1986, pp. 207-211, and the references cited in that
article.
15

In the traditional design of such devices, it is
considered that the width of the air-gap between two
facing teeth should be as narrow as possible in the light
of the technical constraints that stem from manufacturing
20 tolerances in terms of diameter, concentricity,
centering, burring, and other sources of inaccuracy.
T. Kenjo states this clearly on page 30 of the above-
cited work in its chapter entitled "Air-gap should be as
small as possible". That concept has been supported by
25 the theory. The well-known fundamental expression for
calculating force or torque in electromagnetism and
derived from the expression for the magnetic energy
stored in the air-gap, for two sets of teeth in relative
displacement with degree of freedom α states that the
30 torque C that is generated will be proportional to:

$$\frac{dA}{d\alpha} U^2$$

35
where U is the magnetic potential difference applied
between the two sets of teeth, and A is the permeance
between them. In a variable reluctance motor, this can

be constituted by a magnetic potential difference due solely to the ampere-turns generated by one or more coils carrying electric currents, placed in various possible ways, or in a hybrid motor due to the algebraic sum of the magnetic potential difference U_a polarizing the air-gap under the influence of the permanent magnet plus the magnetic potential difference U_{ni} generated by the above-mentioned coil(s).

The derivative of the permeance $dA/d\alpha$ can be developed in the form of a Fourier series, as can the permeance itself:

$$A = a_0 + a_1 \sin(N\alpha) + a_2 \sin(2N\alpha) \ldots$$
$$dA/d\alpha = Na_1 \cos(N\alpha) + 2Na_2 \cos(2N\alpha) \ldots$$

where N is the number of teeth around the rotor, or if the rotor is incompletely fitted with teeth, the ratio $2\pi/$(angular pitch) of the teeth that exist.

The first term of the derivative of this expression relative to α, known as the fundamental term, is $Na_1 \cos(N\alpha)$. In a motor or an actuator for controlling movement, or in a generator from which an accurately sinusoidal voltage is expected, with the number N of teeth being fixed, it is desirable to increase the amplitude a_1 of the fundamental and to reduce as much as possible the amplitudes a_2, a_3, ... of the harmonics $\cos(2N\alpha)$, $\cos(3N\alpha)$, ... The fundamental term of the torque is then given by expression [1]:

$$[1] \qquad C = \frac{dA}{d\alpha} U^2 = Na_1 U^2 \cos(N\alpha)$$

It is well known that the term a_1 increases with decreasing air-gap. Since the torque C is proportional to this term, it would appear to be logical to select an

air-gap that is as small as possible compatible with the
manufacturing method.

For a hybrid motor of ordinary size (known as size "23",
5   giving a diameter $\approx$ 51 millimeters (mm), length $\approx$ 51 mm),
the usual minimum air-gap is about 0.07 mm to 0.08 mm,
giving rise to severe constraints on manufacturing
tolerances and therefore increasing manufacturing costs.
In practice, the air-gap E of conventional motors of this
10   size is always $\leq$ 0.1 mm.

For such a hybrid motor, the maximum potential difference
U_{max} that appears in the above formula for torque is U_{max} =
$U_{ni(max)}$ + U_a. For the above-mentioned size and under
15   steady conditions, the coil provides a maximum potential
$U_{ni(max)}$ = 85 ampere-turns (At) between teeth, for example.
Since the torque due to the current is at a maximum when
$U_a \approx U_{ni(max)}$, U_a is also set to be about 85 At, so U_{max} =
170 At. Ignoring magnetic potential losses in the soft
20   magnetic materials of the stator and of the rotor, the
induction B in the air-gap is given by:
[2] $B = \mu_0 U_{max}/E$.

If it is desired to set a limit of B = 2 teslas (T)
25   because of saturation of the material of the magnetic
circuit, then E = 1.07×10^{-4} meters (m). Thus, an air-gap
of 7×10^{-4} m to 8×10^{-4} m leads to the silicon-iron used as
the soft magnetic material being slightly saturated.
However, when that type of motor is used with a duty
30   ratio of only a small percentage, the ampere-turns could
be increased during the short periods of activity, thus
making it possible to increase the air-gap so as to
remain within the linear region described by equation
[2]. However, in conventional devices, this is not done
35   for the reasons mentioned above: it is preferred to
maximize the derivative of permeance, and thus to have a

small air-gap, and to saturate the magnetic circuit
further.

For example, in the above-cited work by M. Jufer at
5   § 11.19.1 giving the characteristics of a rotary
reluctance stepper motor of the Warner trademark it can
be seen that E = 0.05 mm and U_{max} = (14/5)80 = 224 At,
that is three times the number of ampere-turns that
suffice for raising B to 2 T in the 5×10^{-5} m air-gap.
10   That does indeed serve to increase peak torque, but above
all it generates major distortion in the function C =
$f(\alpha)$ which is far from being a sinewave function. This
is well illustrated in the work by M. Jufer at § 11.11.7
and Figure 11.85. In addition, torque is no longer a
15   simple function of current: the term a_1 itself becomes a
function of U_{max}. In many applications this gives rise to
severe drawbacks, by increasing the instantaneous
modulation of speed and torque ("cogging") due to the
current when the motor is supposed to turning at constant
20   speed and delivering constant torque, and by an increase
in noise level. This also gives rise to poorer
positioning quality in an open loop, particularly when it
is necessary to subdivide the steps.

25   In the light of those drawbacks, an object of the
invention is to provide an electromagnetic device which
is arranged in such a manner as to enable the
manufacturing costs to be reduced significantly and/or to
improve the torque characteristics C = $f(\alpha)$ of the
30   device.

In an application to controlling movement whether in an
open loop or a closed loop, it is advantageous to provide
an electromagnetic device which is such that for each
35   phase it delivers a relationship for torque that remains
substantially sinusoisal up to a magnetic potential value
that is only slightly below the maximum design potential.

The objects of the invention are achieved by the device of claim 1.

5 The electromagnetic device of the invention which is of a size that enables a maximum magnetic potential U_{max} to be generated of about $1.7 \times 10^{-4} J/\mu_0$, that is about 270 At if J = 2 T, or even more, is characterized in particular in that the width of the minimum air-gap measured

10 perpendicularly to the degree of freedom is selected in such a manner that:

E is approximately equal to or greater than the value of:

15 $$0.7[1 - 5 \times 10^{-4}(U_{max} - 1.7 \times 10^{-4}J/\mu_0)]\mu_0 U_{max}/J$$

when
$$[1 - 5 \times 10^{-4}(U_{max} - 1.7 \times 10^{-4}J/\mu_0)] \geq 0.5$$
or E is approximately equal to or greater than:
20 $$0.35\mu_0 U_{max}/J$$

when
$$[1 - 5 \times 10^{-4}(U_{max} - 1.7 \times 10^{-4}J/\mu_0)] < 0.5$$
or E is greater than 2×10^{-3} m

25
where:

· μ_0 is the permeability of a vacuum;

30 · U_{max} is the maximum magnetic potential difference generated to cause the magnetic field to cross the air-gap E, said potential difference being due:

· either to the ampere-turns alone of the coil(s)
35 feeding the air-gap E;

· or else to the sum of said ampere-turns plus the
magnetic potential difference between the two sets of
teeth in the absence of current, due to a permanent
magnet ("polarization" potential); and

· J is the maximum polarization of the soft magnetic
material used for making the teeth; J is defined by the
usual relationship $B = \mu_0 H + J$ where H is large enough to
reach about 99% of the limit value for J, or indeed, when
taking consideration of relative permeability μ_r, by the
relationship $J = \mu_0(\mu_r-1)H$ (where H is large enough to
generate about 99% of the limit value of J).

For the laminated silicon-iron commonly used as the soft
magnetic material, $J \approx 2$ T.

An in-depth study of the operating conditions of a motor
or generator has shown, surprisingly and against the
general tendency seeking to reduce air-gap size, that in
order to optimize a motor or a generator when sufficient
ampere-turns are available, it is on the contrary
advantageous to increase air-gap size, particularly for
motors or generators in which the maximum magnetic
potential is greater than about $1.7 \times 10^{-4} J/\mu_0$.

In the present invention, it is the product $a_1 U^2$ that
appears in the expression [1] that is optimized, contrary
to all conventional devices where only the fundamental
term a_1 of variation in the permeance of the teeth is
optimized.

In an electricity generator, e.g. of the polarized
variable reluctance type, the voltage is proportional to
$d\phi/dt$ or to $d\phi/d\alpha - d\alpha/dt$. The term $d\alpha$ is the angular
velocity. The flux is the product of a permeance
multiplied by a potential difference; flux variation is
proportional to $a_1 U_a$. When the generator is delivering

current, the current it delivers increases the potential difference between certain sets of teeth, and the relationship again includes a term in a_1U^2, as for a motor, thus leading to the same conclusions on the topic of the minimum air-gap E.

When the soft magnetic material works with induction that is only 2% greater than its polarization J, then variation in maximum induction B as a function of U as given above by relationship [2] lies in a domain that is substantially linear. It is then possible to replace U in the expression for torque by the value BE/μ_0, which gives:

$$[3] \qquad C = \frac{Na_1B^2E^2}{\mu_0^2} \cos(N\alpha)$$

It is clear that it is preferable to increase B, which is a squared term, as far as allowed by the soft magnetic material, while remaining within the specified condition whereby B preferably exceeds J by only 2% or less so as to lose only a small portion of U_{max} in the soft magnetic material. The criteria for selecting this material includes, for example, ease of manufacture, cost, and the operating frequency of the device.

In the present invention, it is necessary to determine how the product a_1E^2 varies and not only how a_1 varies. The factor a_1 is a function of the pitch/air-gap ratio (P/E) of the teeth. This function has been correlated empirically with a power function over a wide domain of variation in P/E. It turns out that for constant pitch P of the rotor teeth (measured along the arc), a_1 is substantially proportional to $E^{-1.42}$ and that this applies as far as ratios of P/E that are less than 10. As a result, the product a_1E^2, and thus C, most surprisingly, turns out to be proportional to $E^{0.58}$ which is an

increasing function. For example, when E is doubled, the term $E^{0.58}$ increases by about 50%. The power 0.58 can vary slightly as a function of the shape of the teeth, but the conclusion remains that the product a_1E^2 is an increasing function of E.

In order to be able to benefit from this advantage, it is clear that it must be possible to increase U_{max} with E, as shown in Figure 7 where the range 25 plots $E = 0.7\mu_0 U_{max}/J$ for two values of J corresponding respectively to a silicon-iron (line 23) of ordinary type, and to one of the best-available materials, namely cobalt iron (line 23'). This value for E thus goes beyond the value which, with small air-gaps, serves to generate induction close to saturation for the soft material used. At low potentials, that is when U_{max} is less than about 114 At for silicon-iron, and as shown in range 24 of Figure 7, air-gap values of less than 5×10^{-5} m apply, corresponding to the practical limits for mechanical embodiment. The air-gap is then determined by considerations other than the above formula, even though the values overlap.

As a result, the invention applies to devices of size greater than about 40 mm to 50 mm in rotary versions. For such devices, U_{max} is greater than $1.2 \times 10^{-4} J/0.7\mu_0$ approximately, as shown by the range 25 in Figure 7.

In practice, if very high operating quality in terms of controlling movement is not required, it is possible for example to accept B at the tips of the teeth becoming greater than J by 5%. E is then defined by the formula $\mu_0 U_{max}/1.05J$ if potential drop in the soft material can be tolerated. However, in reality, the potential loss in the soft material is no longer negligible, particularly at the teeth, so the potential difference which remains between the two sets of teeth is only about 84% of U_{max}, for example. It is thus possible to define the limit

value for E by $0.84\mu_0 U_{max}/1.05J$, that is $E \geq 0.8\mu_0 U_{max}/J$.
Nevertheless, with certain soft magnetic materials, more
ampere-turns are lost at $B = 1.05J$, and it is reasonable
to accept a loss of 30% of the potential generated in
5 said soft material without excessively influencing the
linearity of torque as a function of applied or generated
electrical power (depending on whether the device is a
motor or a generator), such that only 70% of U_{max} remains
between the teeth, that is $0.7U_{max}$.

10

The preferred value for E in accordance with the
invention thus obeys the following relationship:

[4] $E \geq 0.7\mu_0 U_{max}/J$

15

It should be observed that the progress of air-gaps in
conventional devices also increases with U_{max} since the
increasing size of such devices gives rise to an increase
in the tolerances required for manufacture, centering,
20 and the clearance necessary to accommodate thermal
expansion. Nevertheless, in conventional devices,
attempts are always made to keep the air-gap as small as
possible, which means that in conventional machines, air-
gaps increase as a function of U_{max} less steeply than in
25 above relationship [4]. It is thus possible to improve
existing devices by increasing their air-gaps without
thereby reaching the preferred value of $E \geq 0.7\mu_0 U_{max}/J$.

In this respect, for devices of increasing size, capable
30 of generating high values for U_{max}, the length of the soft
material magnetic circuit can give rise to losses that
increase but that remain acceptable in certain
applications (e.g. traction motors), so that it is
possible to accept a reduction in the value of the
35 coefficient of $\mu_0 U_{max}/J$. This attenuation coefficient can
be defined by the following expression:

$$E \geq 0.7\mu_0 U_{max}/J$$

where

$$k = 1 - 5\times10^{-4}(U_{max} - 1.7\times10^{-4}J/\mu_0)$$

with the condition that $k \geq 0.5$.

Since air-gaps E in conventional devices do not exceed 1 mm to 2 mm, it is possible to improve the performance of large devices by increasing the air-gap beyond 1 mm to 2 mm, even while remaining below the value given above by relationship [4] as being the optimum value for the air-gap.

It is remarkable that with increasing air-gap and at constant induction in the air-gap, the loss of magnetic potential in the soft materials of the stator and the rotor remains substantially constant. Thus, compared with the total magnetic potential difference U_{max}, this loss is reduced, thereby linearizing the characteristic of the device giving torque as a function of applied electrical power. Like the torque, the applied electrical power has a term in U^2. Conversely, in prior art devices of the kind cited above (M. Jufer § 11.19.1) potential loss in the soft material can be several times the potential difference that exists between the tips of the teeth. No linearity can be expected between torque and the applied power in conventional devices.

By way of example, in an embodiment concerning a hybrid motor, that is a motor that has a permanent magnet, if the soft magnetic material is a silicon-iron characterized by J = 2 T and for which each pole piece of the stator generates 160 At under the effect of the current, U_a must be selected to have a value that is likewise about 160 At, giving $U_{max} \approx 320$ At. The dimensioning rules applied to such a motor leads to a

value for E of 1.6×10^{-4} m or 0.16 mm, which value is considerably greater than that corresponding to the prior art for movement control devices.

5 Other characteristics, objects, and advantages of the invention appear from the claims, the description given below, and from the accompanying drawings. By way of example, the drawings show two embodiments of motors of the invention and how they are dimensioned.

10

In the drawings:

· Figure 1 is an axial section view of a first embodiment of the invention, in particular for a hybrid motor, the

15 section being on line I-I of Figure 2;

· Figure 2 is an axial face view of the Figure 1 motor;

· Figure 3 is a detail view on a larger scale showing a

20 portion of the teeth of a motor of the invention;

· Figure 4 is an axial face view of a variant of a hybrid motor of the invention;

25 · Figure 5 is an axial face view of another embodiment of the invention, in particular of a variable reluctance motor or generator;

· Figure 6 is an axial face view of a variant variable

30 reluctance motor or generator of the invention; and

· Figure 7 is a graph showing the optimum relationship between minimum air-gap E and maximum magnetic potential U_{max} in devices of the invention.

35

In Figure 1, the hybrid motor of the invention comprises a stator given overall reference 1 and a rotor 2 mounted

14

on a shaft 3. The shaft 3 is housed in bearings (not
shown) supported in a motor casing (likewise not shown)
which serves to center the shaft 3 relative to the stator
1.

5

The stator 1 has a magnetic circuit portion 4 made out of
a stack of silicon-iron laminations, for example.
Electric coils such as 5 are mounted on the stator in a
manner described below. The rotor 2 has two pole pieces

10   6 and 7 each constituted by a stack of silicon-iron
laminations, for example, these pole pieces presenting
respective coaxial hollows 8 and 9, in particular to
reduce the inertia of the rotor while not affecting its
magnetic properties. A permanent magnet in the form of
an annular disk 10 is placed between the pole pieces 6

15   and 7 so as to form an assembly in axial alignment
secured to the shaft 3. The magnet 10 is magnetized
axially and its thickness in this direction is very small
compared with its outside diameter.

20

Figure 2 shows the rotor and the stator together when
seen in the axial direction. In this figure, the
magnetic circuit portion 4 of the stator 1 comprises an
essentially annular portion 11 and a plurality of pole

25   pieces such as 12 extending radially towards the inside
of the stator. Each of the pole pieces 12 has a body
portion and a set of teeth 13 in the form of a plurality
of teeth such as 14. Electric coils such as 5, 5', etc.
are prefabricated on insulating supports such as 15, 15'

30   and are mounted on the body portions of the corresponding
pole pieces. These pole pieces are of uniform length in
the axial direction and of uniform length in the radial
plane of the motor, such that the coil and insulating
support assemblies can be put into place on the pole

35   pieces from the inside of the stator. The insulating
supports 15, 15' are somewhat elastic and can be provided
on their insides with projecting portions 16 arranged to

penetrate into corresponding notches 17 in the flanks of the pole pieces so that the coils are retained on the pole pieces. The shape of these pole pieces, and in particular the lack of any flaring towards the teeth

5 makes it possible to perform assembly in the manner described and avoids any need to wind the coils in situ which would be considerably more complicated and expensive.

10 The outside shape of the portion 4 shown in Figure 2 is octagonal in cross-section, the stator having eight pole pieces 12. Such an octagonal shape makes it possible to provide fixing and centering openings or bores 18 in the corners of the polygon so as to avoid weakening the

15 magnetic circuit and avoid any corresponding risk of saturation occurring in a location of reduced section.

The hybrid motor of Figure 4 is very similar to that of Figure 2, except that it has four pole pieces 12'. The

20 use of two coils 5" and 5"' per phase instead of four as in the embodiment of Figure 2 makes it possible to apply twice as much electrical power per coil since each coil has more copper. This makes it possible to generate almost twice as many ampere-turns per coil than are

25 possible with the Figure 2 disposition having eight poles and eight coils.

At its periphery, the rotor 2 has a series of teeth 19 forming a set of teeth 14 at uniform pitch.

30

Figure 3 shows a detail of the teeth 20 of the rotor placed facing the teeth 13 of a pole piece of the stator. The shapes and dimensions of the teeth 14 and 19 and of the respective adjacent hollow portions 21 and 22 are

35 similar, even though the stator teeth are associated with deeper hollows than the rotor teeth. Two teeth placed facing each other form between them an air-gap of width E

in the radial direction, where the value E is small compared with the height of the teeth. The special feature of the sets of teeth shown in Figure 3 consists in particular in the shape of the hollows 21, 22 which

5 are preferably essentially parabolic in the radial plane of the motor, with the angle β formed between the tangents to the profiles of the teeth at the corners thereof having a value of about 110°, that is a value lying in the range 95° to 125°, and preferably in the

10 range 105° to 115°. This shape turns out to be particularly advantageous when in the presence of high induction since the loss of potential in the tips of the teeth is significantly reduced while still having good depth (d) for the teeth.

15

The dimensioning of the air-gap in accordance with the invention depends on the maximum magnetic difference $U_{ni(max)}$ equal to the ampere-turns of the coil(s) feeding the air-gap E. This potential is limited by the maximum

20 current i that the motor can accept either under steady conditions or under low duty-ratio conditions, in which case the magnitude of the current can be a multiple of the maximum current under steady conditions.

25 In the embodiments of Figures 1, 2, and 4 (hybrid motors), the permanent magnet is selected and dimensioned in such a manner as to cause it to generate approximately the same potential difference in the air-gap as is generated by the maximum current, that is $U_a \approx U_{ni(max)}$.

30 The maximum potential difference between facing teeth is thus $U_{(max)} = 2U_{ni(max)}$.

For the above-mentioned motor using a silicon-iron magnetic circuit characterized by J = 2 T and optimized

35 for steady operation, a coil can generate $U_{ni(max)} \approx 160$ At. In applying the above-described relationship $E \geq 0.8\mu_0 U_{(max)}/J$, this gives $E \geq 1.61\times10^{-4}$ m. It would not be

appropriate to take a value much greater than the lower limit, e.g. 2.2×10^{-4} m, that is 37% greater, except under circumstances where excellent linearity and a very low distortion content in the torque relationship for each phase is required, since a larger gap is to the detriment of maximum torque. The maximum induction in the air-gap and in the tips of the teeth would be about 1.8 T in the above example.

Nevertheless, it is advantageous to remain in a range of values as defined by the relationship:

$$0.7 \mu_0 U_{(max)}/J \leq E \leq 1.1 \mu_0 U_{(max)}/J$$

The upper limit is selected empirically so that excellent linearity with loss of maximum torque being less than 30% relative to the lower limit E, given the large reduction in potential losses in the soft material.

It should be observed that since the magnet feeds two air-gaps in series, it must generate a potential of 320 At, which is more than enough to compensate for the various losses in the layers for providing protection against corrosion and in the interstices between the laminations. This can easily be achieved with an NdFeB (neodymium-iron-boron) magnet, which in the example motor shown in Figure 4, that is two-phase motor having a total of two stator poles per phase, can have thickness of the order of 1.5 mm, working a little below its maximum BH point. This operating point is adjusted by the length of the rotor poles in the axial direction and by the area of the magnet. The minimum air-gap used in the prior art made it difficult to adjust the operating point of the magnet when using a modern magnet of the NdFeB type close to its maximum BH point; there was often a load line characterized by $B/\mu_0 H = -4$ to -5. That meant that it was

necessary to use a magnet of volume greater than that of the magnet in the present invention (thus costing more).

In motors of the invention, it is advantageous to take
5 steps to reduce the parasitic relaxation torque at 2P×N periods per revolution, where P is the number of phases of the motor and N is the number of teeth of the rotor. This relaxation torque increases with the square of the polarization potential of the air-gap as provided by the
10 magnet, but it also decreases very steeply with increasing air-gap. In order to eliminate it, or at least reduce it where implementation accuracy is not perfect, it is possible in conventional manner to alter the pitch between the teeth in each pole piece of the
15 stator so that the geometrical sum of the vectors representing the 2Pth harmonic due to each tooth is zero.

If the above motor is optimized to operate for a duty ratio of 25%, then the potentials should be doubled and
20 the recommended air-gap would be 0.32 mm. The rate of increase in mechanical power C^2/I, known as "power rate", where I is the moment of inertia of the rotor, would then be more than doubled compared with the prior art which is very surprising given that the smallest possible air-gaps
25 are implemented in the prior art.

In addition to relaxing manufacturing tolerances as compared with ordinary motors or generators, this increase in air-gap width in devices of the invention
30 also makes it possible to obtain numerous advantages in manufacture, such as, for example, the permanent magnet of the rotor can be magnetized while it is outside the stator because of the greater clearance for inserting the rotor into the stator. Such magnetization makes it
35 possible to saturate the magnet better and to avoid permanent deformation due to shock at the instant of in situ magnetization. However, above all, by magnetizing

outside the stator, it is possible to make the rotor of a
motor out of two assemblies each comprising a magnet and
the corresponding pole pieces in the form of an axial
succession extending from an outside pole piece, to a
5   first magnet, to two touching central pole pieces, to a
second magnet, and to an outside pole piece. Under such
circumstances, the magnets can be magnetized in opposite
directions, with the central pole pieces having the same
polarity, e.g. north, so that the outer pole pieces
10   appear as south poles. This ensures that there is no
magnetic leakage between the ends of the rotor and there
is no need to separate the central pole pieces
magnetically as is the case when magnetizing the rotor in
an assembled motor, where the central pole pieces are of
15   opposite polarities.

In the hybrid motor having a four-pole stator and a rotor
with N = 50 teeth as shown in Figure 4, dynamic balancing
of the magnetic forces is not optimum when the rotor has
20   two pole pieces. With three pole pieces very good
balancing is obtained, as explained with reference to the
embodiment shown in Figure 5.

Mention should also be made of the advantage of the
25   invention when it leads to an air-gap that is large
enough to enable the laminations constituting the rotor
and the stator to be cut out simultaneously. This
simplifies manufacture and gives rise to a large saving
in material.
30

Figure 5 shows a pure variable reluctance three-phase
motor, that is a motor having no magnet for polarizing
its teeth, the motor having six pole pieces 12" without
teeth on the stator 1', two per phase, and four teeth 19"
35   on the rotor 2". Interest is increasing again in this
type of motor given modern possibilities for electronic
control. It is usable with electronic switching and, in

the present invention, it can constitute an excellent
servo-control motor since it has no relaxation torque and
no magnetic losses from the rotor in the absence of
current. The moment of inertia of the motor can be much
5   smaller than that of a hybrid motor where the diameter of
the rotor is determined by the area of the magnet needed
to generate the polarization potential. As is usual with
servo-control motors, such a motor is built to
accommodate peak currents that are eight to ten times
10 greater than the current that can be accommodated under
steady conditions.

If the steady current can generate 150 At per coil 5,
then for a motor of the same size as the specific example
15 of a hybrid motor described above, the air-gap must be
dimensioned for a maximum potential of at least 1200 At,
which means that the air-gap E must be at least 0.6 mm,
which is much greater than prior art air-gaps which are
about 0.1 mm or less, depending on manufacturing accuracy
20 and other tolerances.

With only one tooth per stator pole piece and with a
constant air-gap, it is difficult to obtain a low
harmonic content in the permeance function $A = f(\alpha)$. It
25 is more appropriate, for example, to use a cylindrical
rotor co-operating with stator poles having plane ends,
as shown in Figure 5. When two teeth are facing each
other, the air-gap E between their tips thus varies
slightly between a maximum value on either side of a
30 minimum value lying on the axis of symmetry. Under such
circumstances, the air-gap E for use in the claimed
dimensioning formula is the minimum air-gap. The variant
of Figure 6 is similar to that of Figure 5 except that
the rotor 2"' has eight teeth 19"'. The hollows 22"
35 between the teeth can advantageously be parabolic in
shape, for the same reasons as given above for the teeth
shown in Figure 3. Each pole piece of the rotor has a

chamfer 26 at its end so as to reduce induction when going away from the end. The ends 27 of the teeth of the rotor have the same radius as the circle circumscribing the rotor. Each end 28 of the pole piece 12" of the

5 stator is curved with a radius such that when the stator and rotor teeth are facing each other, the air-gap between them varies. In a specific example where the potential U_{max} is 1100 At, the air-gap varies from a minimum E of 5×10^{-4} m to about 1.65 E, that is 8.25×10^{-4} m

10 so as to obtain a relationship for variation of permanence that includes a very low percentage of harmonics.

The invention can be applied to other motor variants, for
15 example motors having the structures mentioned by
T. Kenjo on page 33 Figure 2.19 (linear motor) and page 34 Figure 2.22 (two air-gaps in series), without going beyond the ambit of the present invention.

20 Other possibilities and advantages will appear to the person skilled in the art both concerning manufacture and concerning use of a motor of the invention.